The University of Chicago

DIURNAL VARIATIONS OF COSMIC RAYS ON THE PACIFIC OCEAN

A DISSERTATION SUBMITTED TO THE FACULTY OF THE DIVISION OF THE PHYSICAL SCIENCES IN CANDIDACY FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF PHYSICS
1938

By
JULIAN L. THOMPSON

Private Edition, Distributed by
THE UNIVERSITY OF CHICAGO LIBRARIES
CHICAGO, ILLINOIS

Reprinted from
The Physical Review, Vol. 54, July 15, 1938; Vol. 55, January 1, 1939

The University of Chicago

DIURNAL VARIATIONS OF COSMIC RAYS ON THE PACIFIC OCEAN

A DISSERTATION SUBMITTED TO THE FACULTY OF THE DIVISION OF THE PHYSICAL SCIENCES IN CANDIDACY FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF PHYSICS
1938

By
JULIAN L. THOMPSON

Private Edition, Distributed by
THE UNIVERSITY OF CHICAGO LIBRARIES
CHICAGO, ILLINOIS

Reprinted from
The Physical Review, Vol. 54, July 15, 1938; Vol. 55, January 1, 1939

R. UNIV.
BIBLIOTHEEK
LEIDEN

Printed in U. S. A.

Solar Diurnal Variation of Cosmic-Ray Intensity as a Function of Latitude

JULIAN L. THOMPSON
Ryerson Physical Laboratory, University of Chicago, Chicago, Illinois
(Received May 21, 1938)

The cosmic-ray data collected by A. H. Compton and R. N. Turner on the Pacific Ocean from March 17, 1936 to January 18, 1937 have been analyzed for a possible change with latitude of the solar diurnal intensity variation. A new geomagnetic latitude curve is shown based on these data and designed to remove periodic fluctuations due to unequal distribution of data with time. A method of combining data from a wide latitude range is developed and applied. Solar diurnal variation curves for latitudes ranging from 54.7° N to 40° S (geomagnetic) show no substantial variation in either amplitude or phase. The mean amplitude of the first harmonic of a Fourier analysis is found to be 0.24 percent with time of maximum being 14 hr. 06 min.

THE study of the solar diurnal variations of cosmic-ray intensity at various latitudes, of which a preliminary survey was published previously[1] has now been carried out in more detail. The data used in this study were those obtained by A. H. Compton and R. N. Turner in observations on the Pacific Ocean covering a period of about a year. A Carnegie model C cosmic-ray meter, mounted on the Canadian Australasian Steamship Company's motor ship Aorangi, was carried on 12 voyages between Vancouver, Canada and Sydney, Australia from March 17, 1936 to January 18, 1937. The meter has been described in detail elsewhere[2] and many of the results of the observations previously reported and discussed by Compton and Turner.[3]

The fact that the data at the various latitudes were all recorded by one instrument is a distinct advantage. Experience has demonstrated the difficulty of obtaining results from several meters, even of the same type, which shall be sufficiently consistent for the comparison of variations of small magnitude. Another advantage is that the data for any particular latitude were not obtained continuously, but at intervals distributed throughout the entire period of observation. There are for example on the average 6 days readings in each 2.5° of latitude. Had the meter been operated continuously for this length of time in one zone, and then moved on to the next, several sources of error might easily have influenced the results. Any seasonal change in the variation would have increased or decreased the observed difference due to latitude change, and it would have been difficult to correct equally for any great difference in barometric conditions in the various zones. In addition, slow changes in the constants of the meter itself, if such had occurred, would have been difficult to detect.

There is, however, an unfortunate feature of this method of gathering data for this type of

[1] J. L. Thompson, Phys. Rev. **52**, 140 (1937).
[2] A. H. Compton, E. O. Wollan and R. D. Bennett, Rev. Sci. Inst. **5**, 415 (1934).
[3] A. H. Compton and R. N. Turner, Phys. Rev. **52**, 799 (1937).

study. Since the average cosmic-ray intensity varies by more than 10 percent in going from the latitude of Vancouver or Sydney to the equator, and since this distance is traversed in somewhat less than two weeks, the change in intensity during a twenty-four hour period from this cause is several times as great as the anticipated diurnal variation. Two courses are open to avoid the serious errors introduced by this circumstance: (1) one may, in finding the diurnal effect for a particular latitude, use only data from a latitude zone so narrow that the variation due to change of latitude is inappreciable; or (2) one may endeavor to correct the data for this latitude effect and thus make possible the combining of data from a wide latitude zone. In the present case, the former method is ruled out by the fact that most of the data would be discarded and one would have a hopelessly small amount of data with which to work. This is accentuated by the fact that since the vessel was on a regular schedule, the south-bound trips encountered a given latitude at almost the same time of day every time, and similarly the north-bound trips, giving only portions of the day for which any data would be available at all. Consequently, the method was adopted of correcting the data for latitude effect and then of combining the results from a comparatively wide latitude zone.

Since latitudes are recorded to 0.1°, it is necessary to have average ionization values for each 0.1° if individual readings are to be adjusted.

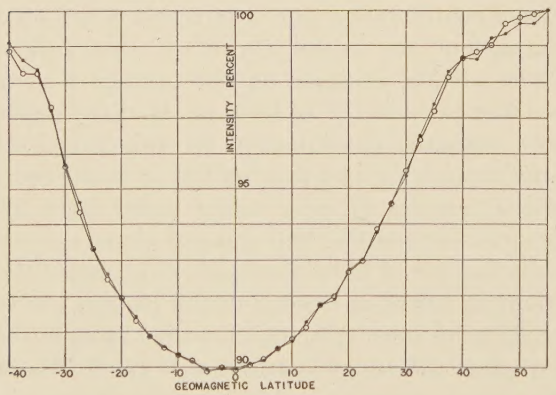

FIG. 1. Mean latitude effect on Pacific Ocean of eleven trips from March 27, 1936 to January 18, 1937. Data of Compton and Turner, showing difference between simple means averaged for each latitude range (black circles) and hourly means over the complete day for each latitude (open circles).

The first necessity in making such a latitude correction is a latitude-effect curve, from which the average ionization value for any latitude may be obtained. The latitudes used in this work are geomagnetic and not geographic, since the latitude effect is in the main a magnetic one. The customary procedure in constructing such a curve is to take the average value of all the data within zones of say 2.5° of latitude and assign that average value to the mean latitude of the zone. This gives a series of points which may be connected by straight-line segments or which may be used to guide in the drawing of a smoothed curve. In this particular case it seemed advisable to treat the data in a somewhat different manner. Since the trips were made on regular schedule, the times of arrival at and departure from principal ports of call were nearly the same on all trips. Thus the total data from all trips were in most 2.5° latitude zones markedly concentrated in certain portions of the day. For example, in the 2.5° zone whose mean latitude is 52.5°, there were 7 and 8 readings each for hours during the night, and only 3 for several of the daytime hours, and this variation was not exceptional. If an average ionization is to be arrived at which will be, as is certainly necessary, independent of any solar diurnal variation, the sampling must be made uniformly from all the hours of the day. To achieve this, the average hourly values were first found, and these in turn averaged over the twenty-four hours in order to fix the true average for the zone. A certain amount of statistical error is introduced by this procedure, since hours with few data are given equal weight with those for which many data are available. It seems clear, however, that where one is restricted to a certain number of data it is more important to eliminate systematic errors as far as possible. The extent to which this has been accomplished may be judged from the comparison of the latitude curve so obtained with that drawn in the more usual manner, as shown in Fig. 1. In general it will be seen that this procedure has been justified, inasmuch as the curve plotted in the usual way shows periodic fluctuations not present in the present curve. Not all of the irregularities are removed, however, and in particular that portion between latitudes 40°N and 54.7°N while im-

proved is still irregular. At 5°S and also at 37.5°S it is definitely more irregular than the original curve.

From the average ionizations obtained in this manner for every 2.5°, values were calculated for every 0.1° by direct linear interpolation. This was done without reference to any curve, although it would correspond to drawing straight-line segments between successive points to form the latitude curve. Despite the fact that the "true" latitude-effect curve must be a smooth curve, the points obtained actually represent the best averages for the various zones, and each point represents about the same number of data. Thus there is no logical way to decide through which points the smooth curve should pass, and linear interpolation offered the best use of the data.

With these values for each 0.1° at hand, each individual hourly value from the original data was adjusted by subtracting the average for the particular latitude at which it was taken. This resulted in transforming the more than 4000 hourly ionization values into hourly deviations from the mean. Insofar as the latitude variation of intensity was concerned, these deviations could be combined from as wide a range of latitudes as desired. The divisions chosen were a 20° zone embracing the geomagnetic equator, two 15° zones to the south and two to the north, and an additional 14.7° zone to the north, extending to but not including Vancouver at the northern extreme, and Auckland, New Zealand at the southern. Data from that portion of the course lying between Auckland and Sydney were not used, since there was but a very small variation in latitude in this portion, and a large variation in longitude.

In each zone except the northernmost, the correction to mean solar time was made by applying the appropriate correction for the mean longitude of the zone, since the variation of mean solar time over the zone was less than one hour. In the case of the zone between 40°N and 54.7°N, since the time variation was 72 minutes, the zone was divided into two parts, and appropriate corrections applied to each part before the data were combined.

It will be noted from the dates given that the period of observation did not cover a full year.

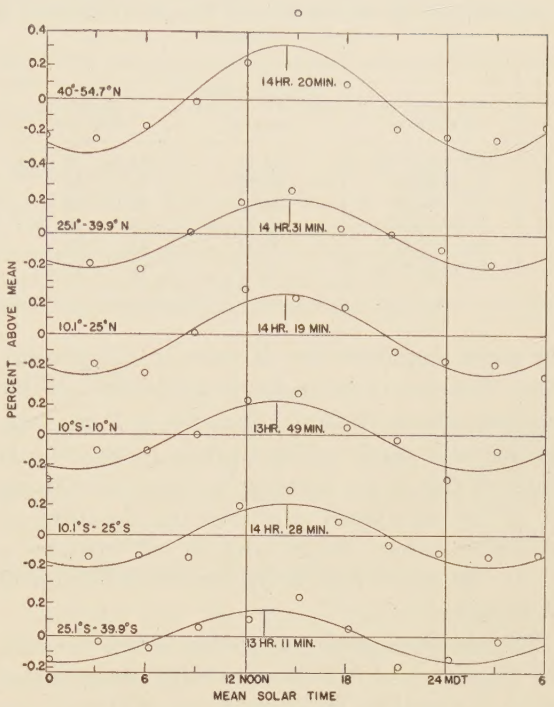

FIG. 2. Three-hourly means and first harmonic curves, showing solar time variations of cosmic rays at different latitudes on Pacific Ocean.

Since it is entirely possible that the diurnal variation may change with the season, the data were further grouped by seasons, and when the mean deviation for each hour had been found for each season, these seasonal averages were in turn averaged to find the yearly mean. In making the seasonal divisions, the solstices and equinoxes were taken as the mid-points of the respective seasons, rather than the dividing points.

From these average hourly deviations, the first harmonic of a Fourier analysis has been calculated, and also the three-hourly averages, both of which have been plotted. These graphs are given in Fig. 2, and a summary of the results in Table I. While it seems by no means necessary to assume an harmonic variation of intensity over the twenty-four hour period, the plotted three-hour means show a reasonably close approach to such a variation. On this assumption it is seen that the amplitude of the solar diurnal variation of intensity is substantially the same for the various latitude zones covered, and of the order of 0.24 percent. If the value of 0.33 percent found for the latitude zone 40°N − 54.7°N be excluded,

TABLE I. *Solar diurnal variation of cosmic-ray intensity at various latitudes.*

	GEOMAGNETIC LATITUDE	AMPLITUDE OF DAILY VARIATION, PERCENT	TIME OF MAXIMUM
1.	40°–54.7° N	0.33	14 hr. 20 min.
2.	25.1–39.9	0.22	14 31
3.	10.1–25.0	0.26	14 19
4.	10 S–10 N	0.23	13 49
5.	10.1–25.0 S	0.21	14 28
6.	25.1–39.9 S	0.17	13 11

the mean amplitude for all zones is 0.22 percent. Since this zone is the region in which the latitude variation shows the least regularity in these data, considerable doubt is justified as to the significance of this larger amplitude. There also seems to be no significant variation in the time of maximum, whose mean value for all latitudes is 14 hr. 06 min., with a maximum deviation of 55 minutes.

These results are in reasonable agreement with the amplitude of 0.20 percent with maximum at noon, reported by Hess and Graziadei[4] from the records of three years continuous observations at 2300 meters altitude. Other comparable results are the 0.19 percent amplitude, maximum at 9 hr. reported by R. L. Doan[5] at Chicago from the records of five meters operating simultaneously over a period of 10 days of exceptionally small barometric variation, and the 0.17 percent, maximum at 11 hr., reported by Forbush[6] from a critical analysis of data from 273 days record taken at Cheltenham, Maryland (geomagnetic latitude 50.4°).

The irregularity in the present data, noted above, occurs just on the "knee" of the latitude-effect curve, and a continuation of the study to much higher latitudes both north and south under the same conditions is much to be desired.

In conclusion, the author wishes to express his thanks to Professor A. H. Compton for suggesting the problem and making available the reduced data which have been used, and sincere appreciation for his helpful discussions during the course of the work.

[4] V. F. Hess and H. T. Graziadei, Terr. Mag. **41**, 9 (1936).

[5] R. L. Doan, Phys. Rev. **49**, 107 (1936).

[6] S. E. Forbush, Terr. Mag. **42**, 1 (1937).

Printed in U. S. A.

A Critical Analysis for Sidereal Time Variations of Cosmic Rays on the Pacific

JULIAN L. THOMPSON
Ryerson Physical Laboratory, University of Chicago, Chicago, Illinois
(Received November 7, 1938)

The problem of distinguishing a true sidereal diurnal variation in cosmic-ray intensity from a seasonal change in the amplitude of the solar diurnal variation is approached from the standpoint of the harmonic dial type of analysis. It is shown that the regular cyclic arrangement of the datum points taken in chronological order serves as a criterion for the presence of the sidereal time variation. Cosmic-ray data taken on the Pacific Ocean during 1936 by A. H. Compton and R. N. Turner are shown to contain no sidereal diurnal component larger than the experimental error.

THE search for evidence as to the reality of a periodic change of intensity of cosmic rays according to sidereal time is made difficult by the presence of the much larger solar diurnal variation. The appearance of a sidereal diurnal variation upon formal analysis of a series of data by no means assures one of its reality. As has been pointed out by Messerschmidt,[1] if there is a seasonal variation in the amplitude of the solar diurnal wave, then when averaged over a period of a year according to sidereal time there will appear a residual variation from this cause having no connection with a true sidereal time period. In discussing this problem at the 1938 Chicago Cosmic-Ray Symposium, however, S. E. Forbush indicated that it should be possible, by the use of the harmonic dial type of analysis, to detect the presence of a true sidereal variation if it is greater than the experimental error.[2]

THE IDEAL HARMONIC DIAL

In this type of analysis, considering only the first harmonic or 24-hour wave, one determines from the data of one day or a small group of days the amplitude and phase of the variation by the usual Fourier analysis. The tip of an imaginary hand on a 24-hour clock dial, pointing to the hour of maximum and having its length proportional to the amplitude, serves to locate a point on the dial which represents these data. This is done for each day or group of days and these points then form a cloud whose mass center will indicate the mean time of maximum and the mean amplitude.[3]

Solar component of constant amplitude

Consider now the type of dial to be expected from an ideal case of solar diurnal variation of constant amplitude

$$c \sin\left(\frac{2\pi t}{T_1}+\alpha\right),$$

where t is the time in solar days and α is the phase angle. T_1, the period in solar days, is, of course, unity. In this case, by use of a solar time dial, all of the points will be found to be coincident and the cloud will consist of but one point which lies at a distance c and angle $\pi/2-\alpha$ from the origin. On the other hand, if there is present only a sidereal diurnal variation of constant amplitude represented by

$$h \sin\left(\frac{2\pi t}{T_2}+\beta\right),$$

where T_2 is the sidereal period in solar days, t has the same significance as before, and β is the phase angle, the points will fall on a circle of radius h concentric with the dial. Combining these two variations and expressing in terms of frequency rather than period we have

$$f(t)=c \sin(2\pi\nu_1 t+\alpha)+h \sin(2\pi\nu_2 t+\beta),$$

where ν_1 and ν_2 are the frequencies in periods per

[1] W. Messerschmidt, Zeits. f. Physik **78**, 682 (1932).
[2] A. H. Compton and I. A. Getting [Phys. Rev. **47**, 817 (1935)] note that a distinction can be made between a sidereal period and a seasonal variation of the solar period by comparing the phase of the apparent sidereal effect in the northern and southern hemispheres. The method here used has the advantage that it does not require data from more than one station.
[3] For a comprehensive discussion of the harmonic dial as used in geophysical and cosmical problems see J. Bartels (a) Terr. Mag. **40**, 1 (1935); (b) Terr. Mag. **37**, 291 (1932).

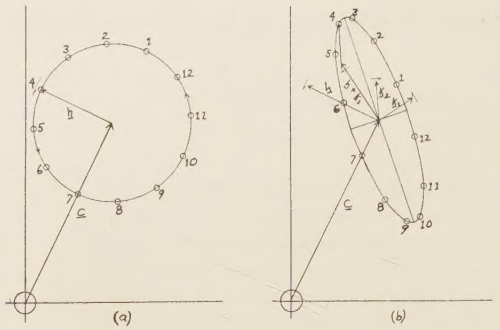

FIG. 1. Periodicities plotted on solar time dial. (a) Combination of solar diurnal and sidereal diurnal variations each of constant amplitude. (b) Combination of solar diurnal variation of harmonically varying amplitude with sidereal diurnal variation of constant amplitude.

solar day corresponding to the periods T_1 and T_2. Since these frequencies are nearly equal we may write $\nu_2=\nu_1+\mu$ so that the expression for the total variation becomes

$$f(t)=c\sin(2\pi\nu_1 t+\alpha)+h\sin(2\pi\nu_1 t+2\pi\mu t+\beta).$$

μ is small compared to ν_1 and to a first approximation what is represented is the sum of two sine curves of equal frequency but with their relative phases varying slowly with the period $1/\mu$. If an arbitrary time origin is chosen, the amplitude of the resultant diurnal variation will be a maximum and equal to $c+h$ when $\alpha=2\pi\mu t+\beta$. When $\alpha+\pi=2\pi\mu t+\beta$ the amplitude will have a minimum value of $c-h$. This will appear on the harmonic dial as a vector of amplitude h revolving with a period of $1/\mu$ solar days about the end point of **c**, as shown in Fig. 1(a). As $\mu=1/365$ this rotating vector will complete one revolution in a solar year. The resultant vector representing the combination of the two variations will therefore show a seasonal phase shift as well as a seasonal change in amplitude. The maximum shift of phase will be $\pm\arcsin h/c$. If data representing this type of variation are plotted on a solar time dial the points will progress regularly around the circle in a counter-clockwise direction. This regular cyclic order of the plotted points is an important characteristic.

Solar component with seasonal amplitude variation

To investigate the effect of a seasonal variation in the amplitude of the solar component let

$$\left(c+2k\cos\frac{2\pi t}{T_3}\right)\sin\left(\frac{2\pi t}{T_1}+\alpha\right)$$

represent a harmonic variation of period T_1 with an amplitude varying with a period T_3. Bartels[4] has pointed out in a similar connection that this is equivalent to three harmonic variations of slightly different periods,

$$\left(c+2k\cos\frac{2\pi t}{T_3}\right)\sin\left(\frac{2\pi t}{T_1}+\alpha\right)$$
$$=c\sin\left(\frac{2\pi t}{T_1}+\alpha\right)+k\sin\left(\frac{2\pi t}{T_1}-\frac{2\pi t}{T_3}+\alpha\right)$$
$$+k\sin\left(\frac{2\pi t}{T_1}+\frac{2\pi t}{T_3}+\alpha\right).$$

If $T_3=nT_1$ this simplifies as follows:

$$\frac{2\pi t}{T_1}-\frac{2\pi t}{nT_1}+\alpha=\frac{2\pi nt-2\pi t}{nT_1}+\alpha=\frac{2\pi t}{nT_1/(n-1)}+\alpha,$$

and similarly

$$\frac{2\pi t}{T_1}+\frac{2\pi t}{nT_1}+\alpha=\frac{2\pi t}{nT_1/(n+1)}+\alpha.$$

Thus there appear variations of three different periodicities, T_1, $(n/n-1)T_1$ and $(n/n+1)T_1$. In the particular case under discussion $n=365$, so that periods appear of 1 solar day, 365/364 solar days and 365/366 solar days. This latter period is one sidereal day which thus in a purely formal manner appears from the analysis of a seasonally varying solar component. On the harmonic dial these two extra periodicities appear as vectors of amplitude k revolving in opposite directions with the period T_3 (one solar year) around the end-point of the solar amplitude vector. It should be noted that there is no seasonal variation of phase introduced thereby, only variation in amplitude.

If the seasonal amplitude variation of the solar component and the sidereal component are both

[4] Cf. paragraph A8 of reference 3(a). The discussion by A. G. McNish [J. Frank. Inst. **215**, 697 (1933)] suggests an analysis somewhat similar to that here described.

present the resulting variation could be expressed by

$$f(t)=c\sin\left(\frac{2\pi t}{T_1}+\alpha\right)+k\sin\left(\frac{2\pi t}{nT_1/(n-1)}+\alpha\right)+k\sin\left(\frac{2\pi t}{nT_1/(n+1)}+\alpha\right)+h\sin\left(\frac{2\pi t}{nT_1/(n+1)}+\beta\right).$$

Since the period of the sidereal wave will be the same as the period of one of the components of the seasonal variation, these may be added together to give a single harmonic component of the total variation. The discussion from this point is considerably clarified by following it in terms of rotating vectors on the harmonic dial.

Let the tip of the constant vector **c** in Fig. 1(b) be the pole, with the polar axis in the direction of **c**, and let k be the common amplitude of the oppositely rotating vectors $\mathbf{k}_1$ and $\mathbf{k}_2$ with position angles of ϕ and $-\phi$ together representing the seasonal amplitude variation of the solar diurnal wave. The sidereal diurnal wave is represented by a vector of amplitude h and position angle $\phi+\delta$. The periods are all one solar year and the time origin is chosen so that $\phi=0$ on the date of the maximum amplitude of the solar diurnal variation.

The sidereal diurnal vector **h** and the vector $\mathbf{k}_1$ rotate in the same direction at a constant angle δ with each other, and may be combined into one vector **r** of amplitude $r=(h^2+k^2+2hk\cos\delta)^{\frac{1}{2}}$ at an angle $\theta=\arctan(h\sin\delta)/(k+h\cos\delta)$ with $\mathbf{k}_1$. We have then two vectors $\mathbf{h}+\mathbf{k}_1$ and $\mathbf{k}_2$ rotating in opposite directions with the same period, having unequal amplitudes and being at an angle θ when $\phi=0$.[5] When $\phi=-\frac{1}{2}\theta$ or $\phi=\pi-\frac{1}{2}\theta$ these two vectors will be parallel and give a maximum displacement from the fixed end-point of **c**. When $\phi=\pi/2-\frac{1}{2}\theta$ or $\phi=3\pi/2-\frac{1}{2}\theta$ the rotating vectors are antiparallel and the displacement from the end-point of **c** is a minimum. This fixes the positions and magnitudes of the major and minor axes of the ellipse traced out by the resultant of both rotating vectors, semi-major axis

$$(h^2+k^2+2hk\cos\delta)^{\frac{1}{2}}+k,$$

semi-minor axis

$$(h^2+k^2+2hk\cos\delta)^{\frac{1}{2}}-k,$$

angle between major axis and **c**

$$\tfrac{1}{2}\arctan(h\sin\delta)/(k+h\cos\delta).$$

A straight line locus will be obtained when the minor axis is zero, that is, when $(h^2+k^2+2hk\cos\delta)^{\frac{1}{2}}=k$. Solving this expression for δ gives $\delta=\arccos(-h/2k)$. This is possible only for $\pi/2<\delta<3\pi/2$ since h and $2k$ are the amplitudes of the sidereal diurnal wave and the seasonal wave, respectively, and essentially positive. If $\delta=0$ the major axis of the resultant ellipse will be parallel with **c**. The semi-major axis will then have a length $h+2k$ and the semi-minor axis h. In any case there will be a seasonal variation in phase as well as in amplitude, and when datum points are plotted they will lie in chronological order around the ellipse or along the straight line. Except when $(h^2+k^2+2hk\cos\delta)^{\frac{1}{2}}<k$ the ellipse will be described in the counter-clockwise direction.

Distinction between real and spurious sidereal diurnal variation

We see from the foregoing that in the case of a simple seasonal variation in the amplitude of the solar diurnal vector, there is no variation in phase, only variation in amplitude on the harmonic dial despite the appearance of two extra periodicities in the analysis. If a sidereal diurnal variation is present, alone or in conjunction with a seasonal variation in the solar amplitude, variation in phase is always introduced, and the plotted points taken in order will always have a cyclic arrangement. Formal analysis in this case will show two extra periodicities which will in general be of different amplitude.

This form of analysis should give definite evidence as to the presence of a true sidereal diurnal component even in the presence of a seasonal variation of the amplitude of the solar component, a case which the familiar method fails to distinguish clearly. With seasonal and sidereal diurnal variations of exactly equal

[5] A discussion of the case of two oppositely rotating vectors of unequal amplitudes will be found in Karl Stumpff, *Grundlagen und Methoden der Periodenforschung* (Springer, 1937), pp. 129–132.

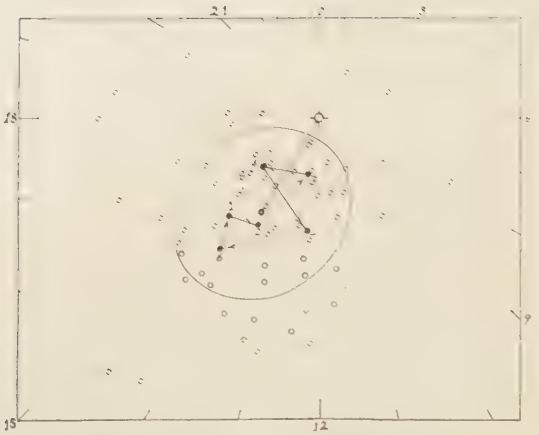

FIG. 2. Solar time dial for 1936 cosmic-ray data from the Pacific Ocean. Light circles, 3–4 day means: heavy circles, all data combined to show chronological order. (Data from Compton and Turner.)

amplitude and opposite phase (i.e., the date on which solar and sidereal diurnal maxima occur together is the date for the minimum in the seasonal variation) we would find, not a canceling of the two effects, but a straight line perpendicular to **c** the mean amplitude vector of the solar diurnal variation. The orderly progression of the datum points along this line would distinguish it from a mere statistical scatter in phase.

THE ACTUAL HARMONIC DIAL

Passing from these ideal cases in which we have assumed no statistical fluctuations to the actual case, we can expect that the larger the relative importance of the statistical fluctuations, the more ill defined the cyclic figures will become. When they reach such magnitude that the figure becomes a random pattern, we can be sure that no sidereal diurnal variation exists which can be distinguished reliably from a seasonal variation in the amplitude of the solar component. In this case, if the computed probable ellipse for the cloud shows a pronounced eccentricity with its major axis approximately in the direction of the solar amplitude vector we can say that a seasonal variation in the amplitude of the solar component is indicated, but can draw no conclusion regarding the reality of a sidereal diurnal variation except that it must be smaller than the probable error of the solar variation.

APPLICATION

The method of analysis outlined above has been applied to data gathered on the Pacific Ocean by Compton and Turner over a period of about 11 months. In view of the fact than an analysis of these data shows no significant change in the solar diurnal variation of intensity with geomagnetic latitude,[6] the data from various latitudes have been combined and examined as a whole for possible evidence of a sidereal time variation.

That portion of the data covering the trips between Vancouver and Auckland was used to compute the constants of the first harmonics of 63 diurnal variation curves; each combined data from three or four days. When plotted on a solar time dial as shown in Fig. 2, a mean amplitude of 0.23 percent is found, with the maximum occurring at about 14 hours. The major axis of the probable ellipse lies within 23° of the mean amplitude vector. Since, however, the ratio of the axes is but 1.17, no predominant variation in either amplitude or phase is conclusively demonstrated. To examine the cloud for cyclic arrangement of the points, time averages are so taken that all the data are represented by six points. These six points when plotted show an irregular figure-eight pattern in which the phase variations are random but the variations in amplitude follow a consecutive order. To be sure that combining data from various latitudes has not masked the effect sought, dials are shown in Fig. 3 for three latitude zones and in each case the random arrangement of the points is evident.[7]

The probable error in phase of these points is

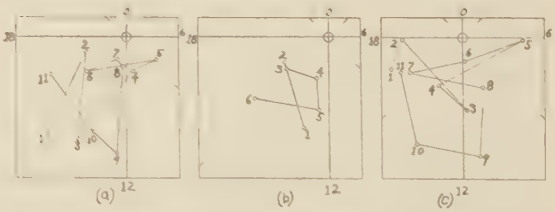

FIG. 3. Pacific Ocean data (1936) by latitude zones. (a) 10°–40°N, (b) 10°N–10°S, (c) 10°–40°S, geomagnetic latitude.

[6] J. L. Thompson, Phys. Rev. **54**, 93 (1938).

[7] It will be noted that the data from the equatorial zone describe a rough figure eight. If real, this would mean a sidereal 12-hour period. The statistical variations of the points are however so great as to make this indication of doubtful significance.

roughly one hour and phase shifts of about this magnitude would be necessary in order to restore the points to a cyclic arrangement. The estimated probable error of phase of one hour corresponds to a probable error in amplitude of 0.06 percent. Within such a probable error, therefore, the present data indicate no significant sidereal diurnal variation. There is however, in the consecutive order of the points according to amplitude, a rather strong indication of an annual change in the amplitude of the solar diurnal variation.

The most specific theory which would predict a sidereal time variation of cosmic rays is that of Compton and Getting,[2] according to which the motion of the earth with the rotation of the galaxy results in a slight excess of cosmic rays from the direction of motion. According to a new calculation by Vallarta, Graef and Kusaka (in this issue, page 1), the amplitude of the sidereal time variation from this cause should be about 0.15 to 0.2 percent, roughly twice as great as estimated by Compton and Getting. The present analysis thus gives significant, though not conclusive, evidence that the sidereal diurnal variation is less than demanded by this theory.

The writer wishes to acknowledge his indebtedness to Professor A. H. Compton for calling this problem to his attention and for his very helpful criticisms of the discussion presented.